Forest Sci., Vol. 28, No. 1, 1982, pp. 31–45
Copyright 1982, by the Society of American Foresters

Predicting the Effects of Rotation Length, Harvest Intensity, and Fertilization on Fiber Yield From Northern Hardwood Forests in New England

JOHN D. ABER
JERRY M. MELILLO
C. ANTHONY FEDERER

ABSTRACT. A generalized computer model of organic matter and nitrogen dynamics in forest ecosystems (FORTNITE) is presented. Data from studies on northern hardwood forests of northern New England are used to adapt the model to simulate this forest type. Validation runs show that the model accurately predicts successional changes in basal area, species composition, leaf production, forest floor biomass, and dead wood mass following clear cutting. The model allows numerous combinations of harvest intensity, species selection, rotation length, and fertilization to be tested. Results indicate that extremely short rotations can reduce yield by as much as two thirds and that fertilization can offset some of this loss. Whole tree harvesting on a 90-year rotation increased yield relative to clearcutting while results from selection cutting were slightly lower. FOREST SCI. 28:31–45.

ADDITIONAL KEY WORDS. Nitrogen cycle, computer model.

THE COMPLEXITY OF FOREST ECOSYSTEMS makes rational management decisions difficult without some means of evaluating the effects of potential programs on all of the major interrelated processes including production, tree growth, decomposition, and nutrient cycling. Computer models offer a logical means of filling this need while also acting as a repository of quantitative information on the system under study and as a valuable guide to future research. Although many models of forest growth based on interspecific or intraspecific competition have appeared (see review by Shugart and West 1980), none of these deal with site conditions as a dynamic part of the model. To date, only two models (Waide and Swank 1977; Aber and others 1978, 1979) have included nitrogen cycling as an integral factor.

Current trends in forest management toward shorter rotations and more intensive harvesting make the results of past permanent plot or other nonintensive experiments inapplicable for management decision making. Intensive management may produce alterations in site quality which will become visible only in the second or third rotation. Impacts on organic matter and nitrogen dynamics in soils may be particularly critical (Aber and others 1978, 1979). Without such

---

The authors are, respectively, with the Department of Forestry, University of Wisconsin, Madison, WI 53706; Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543; and Northeastern Forest Experiment Station, U.S. Forest Service, Durham, NH 03824. This research was supported by grants from the National Science Foundation (DEB-8005081) and the U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. Manuscript received 5 November 1980.

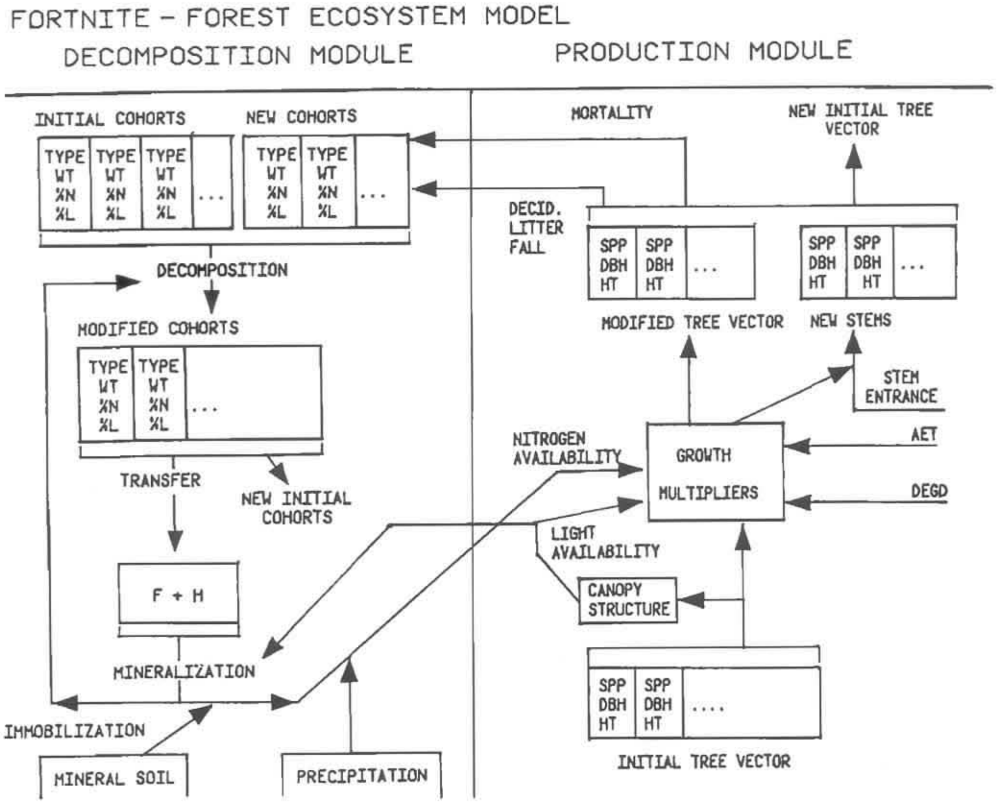

FIGURE 1. Outline of FORTNITE forest ecosystem model. See text for explanation.

field trials, process-oriented computer models of forest ecosystem function may represent the best means of predicting impacts on future productivity. The purposes of this paper are to (1) describe the structure and parameters for a generalized model of organic matter and nitrogen dynamics in forest ecosystems, (2) use data from the literature to adapt this model to the northern hardwood forest type of northern New England, (3) test the accuracy of the model in predicting known developmental trends in this forest type, and (4) estimate the effects of various management practices on yield.

STRUCTURE OF THE MODEL

The model, called FORTNITE, has developed from two previously described models; the JABOWA forest growth simulator (Botkin and others 1972) and a forest floor decomposition model (Aber and others 1978, 1979). The basic unit in FORTNITE is a 10 by 10 m plot. Individual stems and distinct cohorts of litter are followed through time in replicate plots. Replication is required by the stochastic nature of the stem entrance and mortality routines.

The production routine begins (see lower right corner of Fig. 1) with the tallest tree for which a crown is constructed from its height, crown width, and leaf weight per unit crown area. In the equations which follow, the coefficients b2, b3, SLTA, SLTB, LFWT, etc., are defined for each species and describe a species response to environmental conditions (see Table 1 for a list of species used in this version of the model and values for each coefficient). Tree height is a parabolic function of DBH (cm):

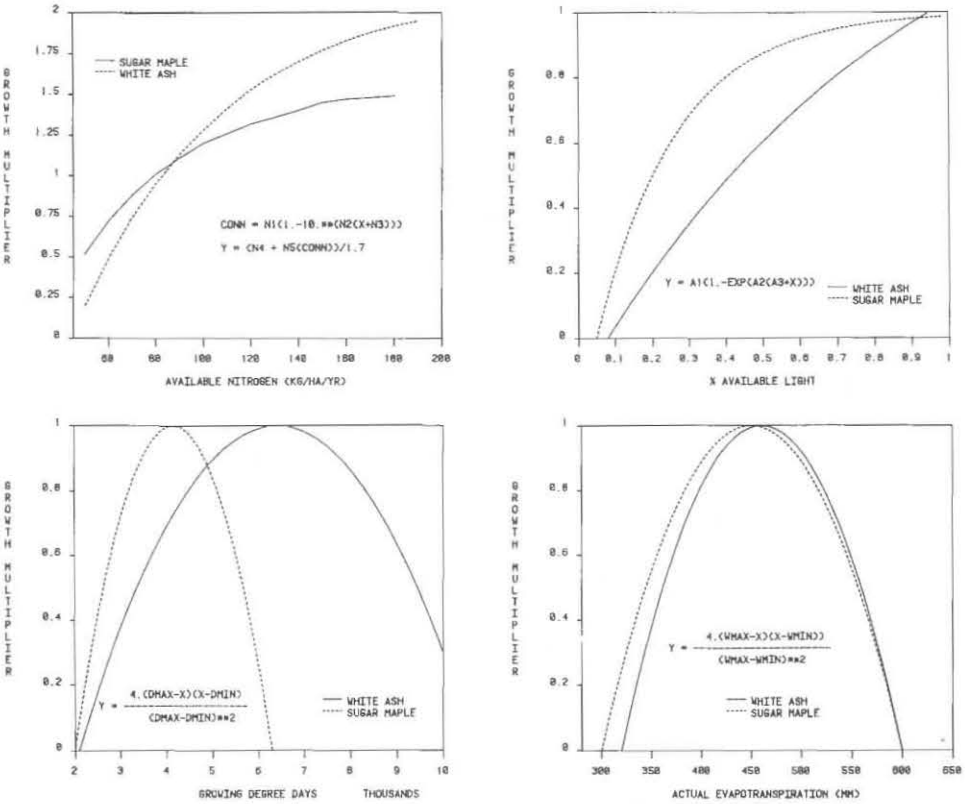

FIGURE 2. Basic form of species responses to environmental parameters using sugar maple and white ash as examples. Equations used to generate lines are shown. Values of the parameters in each equation for each species are given in Table 1.

$$\text{HT (cm)} = 137. + b2 \cdot \text{DBH} \pm b3 \cdot \text{DBH}^2 \qquad \text{(Botkin and others 1972).} \quad (1)$$

Crown width has been shown to be a linear function of DBH

$$\text{CW (m)} = \text{SLTA} + \text{SLTB} \cdot \text{DBH} \qquad \text{(Aber 1976).} \quad (2)$$

From measurements of litter fall under canopies of different species, the average leaf weight per unit crown area can be derived

$$\text{SLA (g/100 m}^2\text{)} = \text{LFWT} \cdot \pi \cdot (\text{CW}/2.)^2 \qquad \text{(Aber 1976).} \quad (3)$$

Light attenuation in forest canopies generally follows the Beers-Lambert law (Monsi and others 1973) which predicts an exponential decay in light intensity with the equation

$$\text{AL} = e^{-\text{SLA}/11250)}. \quad (4)$$

AL is the fraction of full sunlight passing through a canopy with leaf weight SLA (g/100 m^2). The constant 11250 results from comparisons of leaf biomass and percent full sunlight reaching the forest floor in hardwood stands. The total leaf biomass on trees taller than any given stem determines the Al parameter. Actual evapotranspiration (AET) and growing degree days (DEGD) are inputs for each year describing climatic conditions and are the same for each stem. Nitrogen availability is calculated in the decomposition module and is also the same for

TABLE 1. Variables used to describe species response to environmental conditions in FORTNITE and their values for major northern hardwood species used in this set of simulations.

	Species					
Variables	Pin cherry	Yellow birch	Paper birch	Sugar maple	Beech	White ash
b2	70.6	47.8	73.6	50.9	57.8	80.2
b3	1.26	.196	.800	.167	.237	.802
SLTA	.729	.804	.219	.814	.904	.428
SLTB	.044	.069	.097	.078	.095	.074
LFWT	173.	248.	248.	440.	440.	440.
A1	1.55	1.55	1.55	1.	1.	1.55
A2	−1.136	−1.136	−1.136	−4.64	−4.64	−1.136
A3	.08	.08	.08	.05	.05	.08
N1	2.99	2.94	2.79	2.94	2.94	2.99
N2	−.00175	−.00234	−.00179	−.00234	−.00234	−.00175
N3	207.43	117.52	219.77	117.52	117.52	207.43
N4	−5.0	−1.2	−0.6	−1.2	−1.2	−5.0
N5	2.9	1.3	1.0	1.3	1.3	2.9
DMAX	8,000	5,300.	3,700.	6,300.	6,000.	10,700.
DMIN	1,100	2,000.	1,100.	2,000.	2,100.	2,100.
WMAX	600.	600.	600.	600.	600.	600.
WMIN	190.	250.	190.	300.	300.	320.
G	1.1	.7	.6	.5	.5	.5
SAPN	150.	20.	20.	20.	5.	5.
AGMX	20.	200.	80.	200.	300.	100.
RTST	.5	.8	.8	1.0	1.0	1.0

each tree. All four of these variables are converted to growth multipliers of the form shown in Figure 2. The AET, DEGD, and AL growth multipliers are taken directly from the JABOWA model (Botkin and others 1972). The nitrogen multiplier is adapted from an extensive set of fertilizer trials carried out as part of a now classic study on the nitrogen nutrition of northeastern hardwoods (Mitchell and Chandler 1939, Aber and others 1979). These are multiplied together with a maximum potential diameter increment G (cm/yr) to yield realized growth. The same multipliers are also multiplied together and then multiplied by a maximum potential sapling establishment rate (SAPN) to determine the number of new stems per species. The SAPN value for each species is obtained from reproductive potentials (for stems over 0.5 cm DBH, not for seedlings which would be much higher) determined by field studies (Barrett and others 1962, Curtis and Rushmore 1958, Eyre and Zillgitt 1953, Leak and Wilson 1958, Marks 1974, Marquis 1965).

Mortality is a probabalistic function of diameter increment and maximum age (AGMX) (Botkin and others 1972). If diameter increment (cm/yr) is greater than 0.01, the probability of mortality is

$$4.0/\mathrm{AGMX}. \tag{5}$$

If diameter increment is less than 0.01, this probability increases to 0.37. This represents a two-level mortality function with a threshold effect of growth rate which is similar to the steep exponential relationship revealed by field studies (Dale 1974) and used in other models (Monserud 1976).

Litter input to the decomposition module is a function of both mortality and live tree biomass. Leaf biomass as calculated for each tree (see equations 2 and 3) is deposited annually into one of six classes representing the six most important hardwood species. Leaf litter from the species representing each class has been shown to decompose and immobilize nitrogen at very different rates (Melillo and others 1981). Annual fine root litter is very difficult to estimate and has been measured in only one hardwood stand in the northeast (McClaugherty and others 1980). In that stand, root litter was approximately 1.3 times leaf litter. We have assumed that this ratio will be altered in accordance with the root-shoot ratios measured for different species (Bormann and Likens 1979, p. 121) and by changes in forest floor biomass. The equation used to calculate fine root litter production per tree as a function of leaf litter production of that tree is

$$\mathrm{FRL} = 1.3 \cdot \text{leaf litter} \cdot \mathrm{RTST} \cdot \mathrm{FHFAC} \tag{6}$$

where RTST is a species-specific root-shoot ratio and FHFAC is the current weight of the F+H layer as a fraction of the steady-state weight. Annual twig litter has also been studied only rarely, but in a comprehensive effort, Christensen (1977) has shown this to be a function of stand basal area for hardwood forests in Europe. The equation derived from his results is

$$\text{Twig (t/ha)} = \text{the lesser of 1. and (basal area (m/ha)/40.).} \tag{7}$$

Large woody litter, which occurs only as a result of tree death, is calculated using dimension analysis equations of Whittaker and others (1974) and is distributed into 10 size classes in 10-cm diameter increments. Woody root litter is all placed in a single category. Altogether, up to 19 categories of litter (6 types of leaves, 10 sizes of wood, fine roots, twigs, woody roots) can be generated in a single year.

In the decomposition module, each type of litter is converted to a litter cohort with decomposition dynamics determined either by its lignin and nitrogen content (leaves, twigs, fine roots) or by its size class (woody litter). In the former, percent weight loss per year is

$$K = 0.79 - 0.03(L{:}N) \qquad \text{(Melillo and others 1982)} \tag{8}$$

where L is initial percent lignin and N is initial percent nitrogen content in the fresh litter of that type. Percent weight loss in woody litter is calculated as

$$K = 0.13 - 0.014 \cdot \mathrm{DIAM} \tag{9}$$

where DIAM is the mean diameter of the size class.

Decomposing nonwoody litter immobilizes nitrogen also as a function of its nitrogen and lignin content (see Aber and Melillo 1982a for equations used and their derivation). Aboveground wood does not immobilize nitrogen until only 20 percent of its initial weight remains, at which point it transfers to a new cohort of well-decayed wood which decomposes and immobilizes nitrogen in line with its lignin and nitrogen content (Eshleman and others 1979, 1980). Woody roots do immobilize and decay at the rate measured by Eshleman and others (1980). However, the amount of this material in the forest floor is very small and does not have a large impact on the model.

In each modeled year, the decay constant (K, equation 9) and nitrogen immobilization calculations are used to decrease cohort weight and increase nitrogen content. This produces the set of modified cohorts shown in Figure 1. As the weight of a given cohort declines and its nitrogen concentration increases, that cohort approaches the point at which net mineralization will begin (generally around 2 percent N, see Aber and Melillo 1982a for equation used and derivation). When this occurs, the remaining weight and nitrogen is transferred to the F+H layer compartment. The nontransferred cohorts become the initial cohorts for the next year's simulation. A single litter cohort may be present as litter for one or many years depending on the type of material and its decay rate, so the total number of cohorts in the decay process at any one time is usually much larger than 19. Separate cohorts of the same material at different stages of decay are never combined. Thus, several cohorts of the same type of litter may be present at any one time.

Nitrogen mineralization occurs from the F+H compartment in proportion to weight loss which is a constant 9.6 percent per year (Aber and others 1978) times a decay multiplier (DCMLT) which increases decomposition under canopies with low leaf area.

$$\text{DCMLT} = 1. + 1.5 \cdot \text{sqrt}[1. - \text{leaf weight (t/ha)}/2.8)]. \qquad (10)$$

This simulates the response to disturbance (Bormann and others 1974). Nitrogen availability for computing next year's growth is the total mineralized from the F+H layer minus the immobilization demands of the litter cohorts plus 5 kg/ha from precipitation (Likens and others 1977) and an estimated 10 kg/ha mineralization from the mineral soil. The mineral soil compartment is the most poorly defined component of this model.

Nearly all of the data for variables used in FORTNITE are taken directly from field research. However, a model of this complexity cannot be expected to accurately reproduce total system dynamics without a certain amount of "tuning." Three variables were used to provide a small amount of flexibility for this tuning operation: (1) the G variable defining maximum potential diameter increment, (2) the fine root litter production equation, and (3) the decay multiplier. The values arrived at for G are quite reasonable (Curtis and Post 1964, USDA Forest Service 1965, Aber 1976). The decay multiplier and fine root equation represent poorly understood processes and their reasonableness is difficult to assess.

A complete line-by-line description of FORTNITE along with a listing of all input parameters and sample outputs is given in Aber and Melillo (1982b). Space does not allow a more thorough discussion here, but readers are reminded that the projections presented will be no more accurate than the underlying structure and data used in the construction of the model.

MODEL VALIDATION

One major purpose of constructing a model of this type is to apply it to previously untested management practices to see their effects in minutes rather than decades. However, we can never be sure that the model will be totally accurate under a set of conditions different from those in which the data from which it was constructed were collected. The best means of testing the basic accuracy of a model is to use it to predict changes in variables not used in its construction. The equations used in FORTNITE relate processes such as growth, mortality, and entrance of stems, litter fall quantities per stem, and decomposition dynamics to external climatic factors and internal stand canopy structure and nitrogen availability. No constraints are placed on system-level variables such as total live biomass or litter biomass, total rate of production, total light absorbance, and so forth. These values result from the interactions of the modeled processes as modified by the three variables used to "tune" the entire model. The accuracy of the model's predictions for these system-level parameters indicates its overall performance in reproducing total system function.

Figure 3 shows the model's predictions for basal area changes through time following clearcutting compared with data from various sources for northern hardwoods in New England. The data of Marks (1974) and Marquis (1967) combined with the highest values obtained by Curtis and Post (1964) describe the

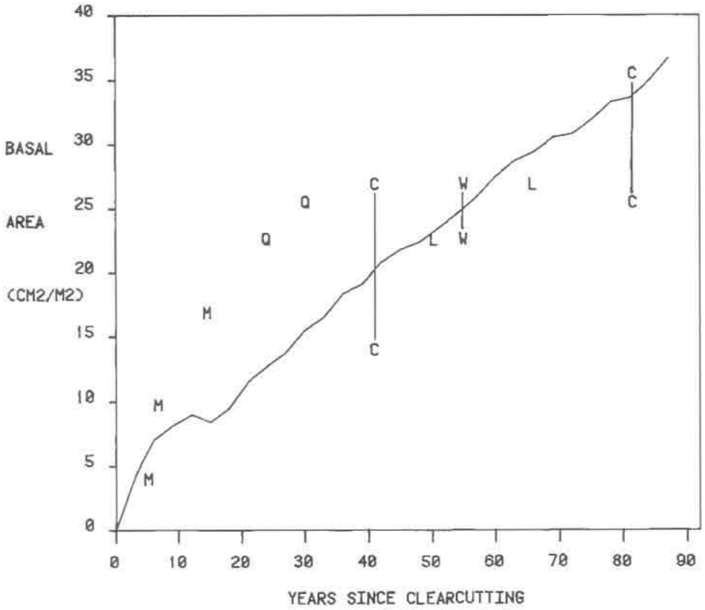

FIGURE 3. Predicted rate of basal area accumulation plotted against measurements by several authors. Lines between letters represent range of estimates. Letters are: M (Marks 1974), Q (Marquis 1967), C (Curtis and Post 1964), L (Leak and others 1969), W (Whittaker and others 1974).

pattern for very high quality sites. The models' projections lie between this upper curve and a lower bound set by Curtis and Posts' poorest site index, very close to data of Leak and others (1969) and Whittaker and others (1974) for more average conditions. Basal area increment projected by the model is in line with the 0.4 cm2/m2/yr estimate for sawtimber stands presented by Leak (1979).

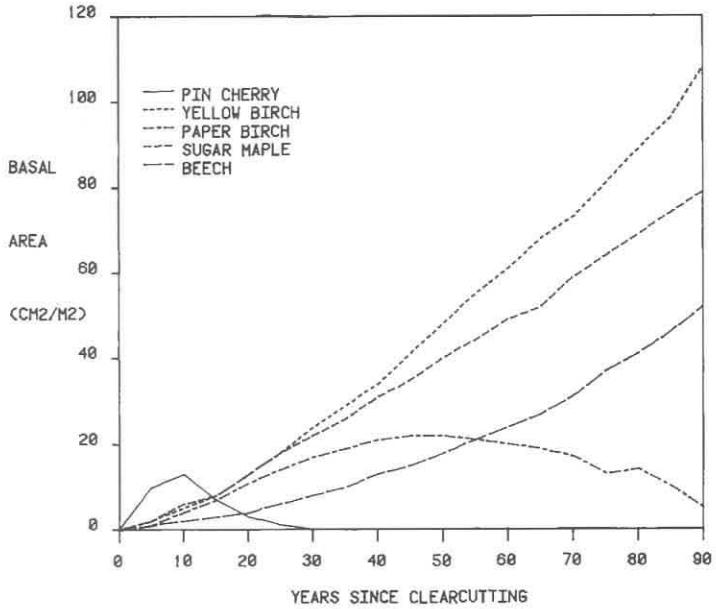

FIGURE 4. Successional changes in basal area by species following clearcutting as predicted by FORTNITE.

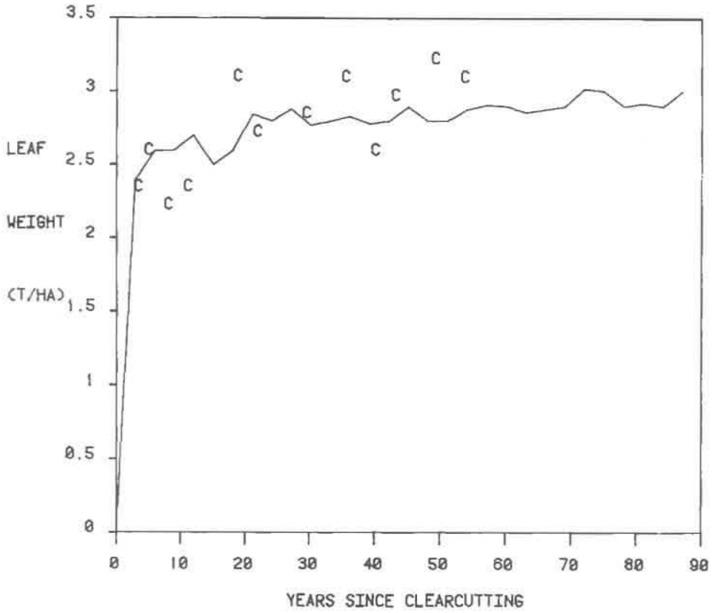

FIGURE 5. Measured (c) and modeled (line) successional changes in leaf production following clearcutting. Data from Covington and Aber (1980).

Figure 4 presents predicted changes in relative basal area by species through time. These follow generally recognized trends (Marks and Bormann 1972).

Figure 5 shows similar agreement between modeled and measured changes in total leaf production following clearcutting. Both basal area and leaf biomass show rapid early rises followed by a leveling off (basal area) or a brief decline (leaf biomass) after year 10. This is due to vigorous growth and early mortality of pin cherry (*Prunus pennsylvanica*), the dominant early successional species in this forest type in New England (Marks 1974). Its rapid decline in the model is largely due to its nitrogen demanding behavior and temporal changes in nitrogen availability (Covington and Aber 1980).

Accurate prediction of leaf production is crucial. This determines fine root litter input which together with leaf litter produces most of the input to the forest floor. Leaf biomass also determines the decomposition multiplier which affects nitrogen availability and forest floor dynamics.

Covington (1980) has measured changes in forest floor biomass through time following clearcutting. His data and the models projections are shown in Figure 6. The projection shows a general agreement with the data but a somewhat faster decline following cutting to a higher minimum. Recovery to steady state conditions is also somewhat slower. In our earlier forest floor model (Aber and others 1978), an external decomposition multiplier was inserted to force agreement between model and data. In FORTNITE, the multiplier is a function of total leaf weight and so results from biologically meaningful feedbacks within the model. It is difficult to explain how the forest floor could continue to decline for 20 years when leaf and presumably fine root litter recover very rapidly. Changes in the distribution of fine root litter or in the rate of mixing between forest floor and mineral soil could be important here. The degree and timing of decline and recovery in forest floor biomass is crucial to projections of management effects.

A final comparison is between modeled and measured (Roskoski 1980) changes in total dead wood biomass (Fig. 7). Again, agreement is very good.

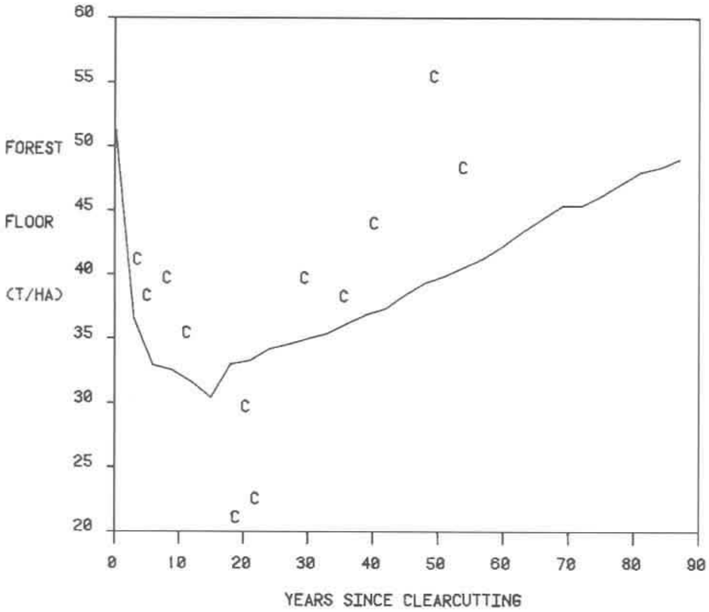

FIGURE 6. Measured (c) and modeled (line) successional changes in forest floor biomass. Data from Covington (1980).

MODEL PROJECTIONS

Aber and others (1979) presented estimates for total production and yield from incompletely linked JABOWA and forest floor models for seven combinations of harvesting intensity and rotation length. A crucial missing factor in that effort was the potential for feedbacks between reduced production and reduced litter

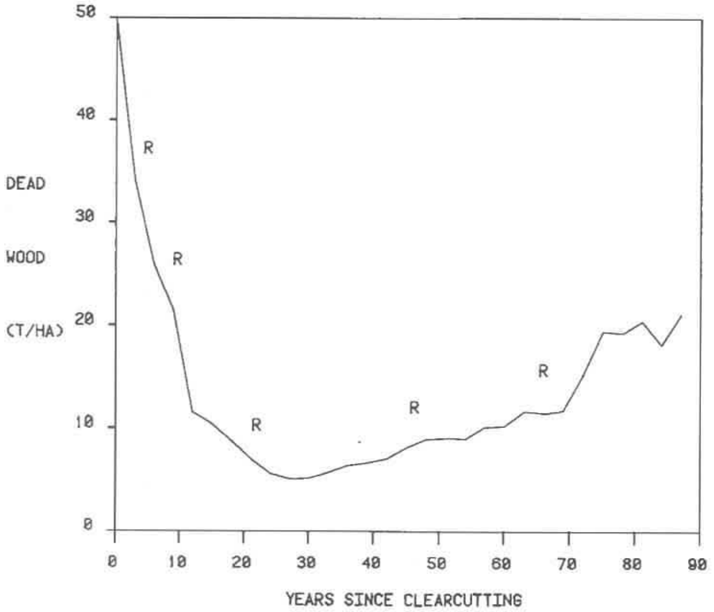

FIGURE 7. Measured (c) and modeled (line) successional changes in dead wood biomass. Data from Roskosky (1980).

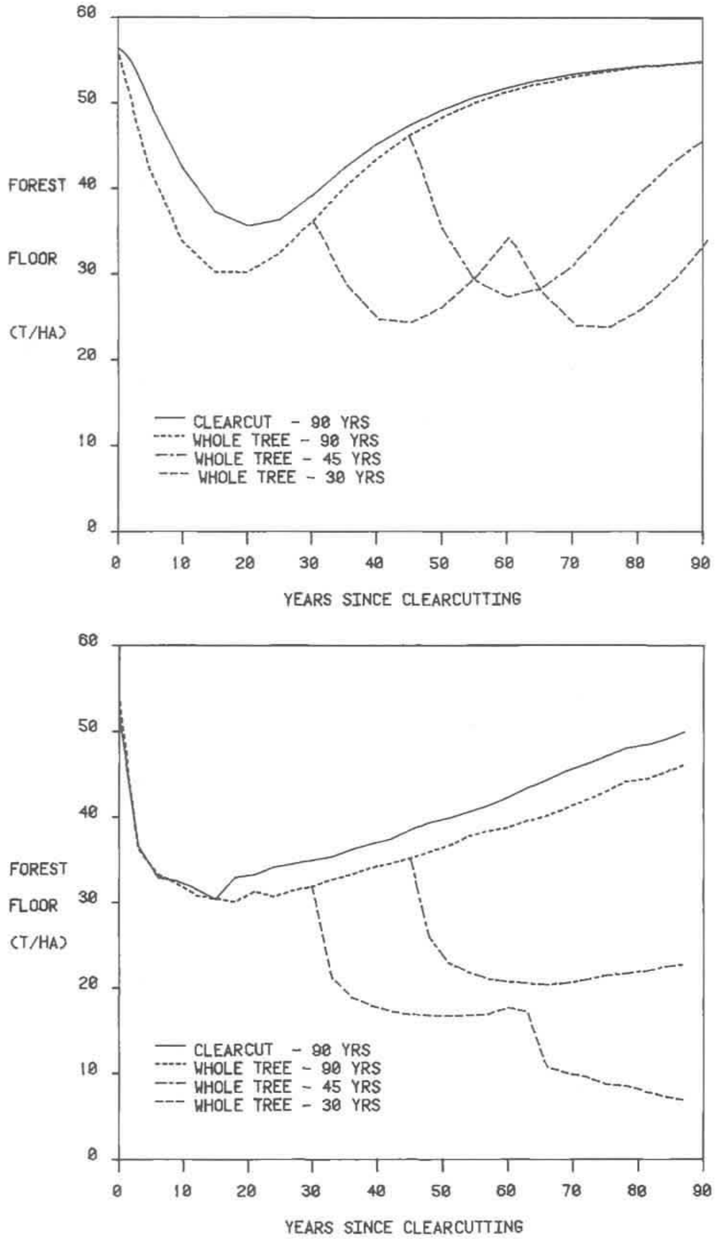

FIGURE 8. Changes in forest floor biomass predicted for 4 harvesting treatments by an earlier forest floor model (upper) and by FORTNITE (lower).

fall resulting in further reductions in forest floor biomass and nitrogen availability. These feedbacks are included in FORTNITE. Figure 8a shows changes in forest floor biomass for clearcutting on a 90-year rotation and whole tree harvesting on one 90-year rotation, two 45-year rotations and three 30-year rotations as predicted by the earlier model. Figure 8b has projections for the same treatments by FORTNITE. The major difference is that successive short rotation harvests cause successive declines in forest floor biomass under FORTNITE while the forest floor

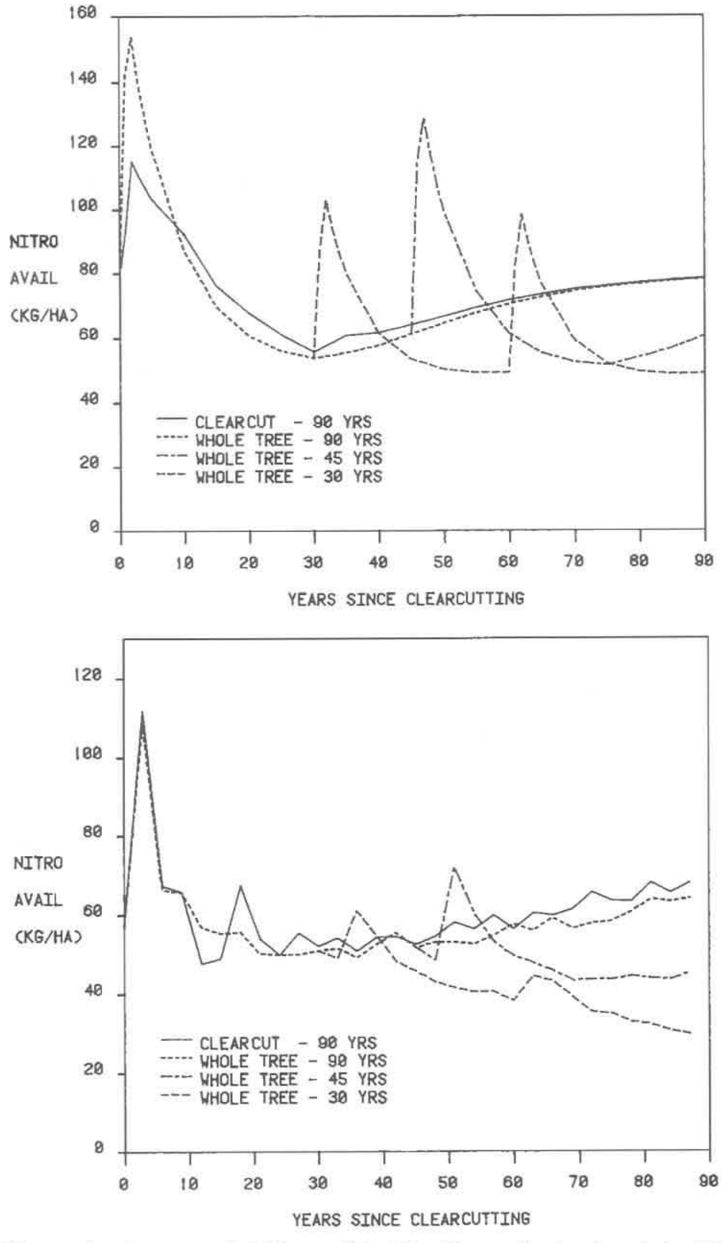

FIGURE 9. Changes in nitrogen availability predicted for 4 harvesting treatments by JABOWA using nitrogen availability data from the earlier forest floor model (upper) and by FORTNITE (lower).

leveled off in the second or third rotation under the previous model. Nitrogen availabilities (Fig. 9) show similar but less pronounced differences.

Table 2 lists total yields for 90 years for all seven harvesting regimes in the earlier paper as predicted by FORTNITE. Although intensive harvesting on long rotations increases yields over conventional clearcutting, short rotations can severely reduce yields. It should be remembered that nitrogen availability here includes 15 kg/ha/yr from precipitation and mineralization in the mineral soil.

TABLE 2. Predicted yields for various silvicultural practices in northern hardwood forests.

Type of harvest	Rotation length	Rotations	Yield		
			Control	1 FERT[1]	2 FERT[1]
	Years	*Number*	*t/ha/90 years*		
Clearcut	30	3	94.4		
	90	1	163.6	188.0	225.2
Whole tree	9	10	52.7		
w/o pin cherry	9	10	38.4		
	30	3	105.0	132.6	172.5
w/o pin cherry	30	3	132.3		
	45	2	140.4		
	90	1	177.1	267.6	282.9
w/o pin cherry	90	1	228.9		
Complete forest	30	3	127.7		
	45	2	175.3		
	90	1	217.0		
Diameter limit					
20 cm lower limit	9	10	151.1		207.5
40 cm lower limit	9	10	144.8		179.8
Selection					
Yellow birch 20 cm lower limit, all others clearcut	9	10	83.8	208.8	288.0
Sugar maple 20 cm lower limit, all others clearcut	9	10	147.6	185.4	242.1

[1] 1 FERT refers to one 100 kg/ha nitrogen addition per 30 years, 2 FERT is two 100 kg/ha additions per 30 years.

Successional patterns in the latter remains the largest unknown in these simulations and could alter the projections significantly.

A number of other silvicultural practices can be simulated with FORTNITE. A selection of these are listed in Table 2. A very extreme 9-year whole tree rotation produces even lower yields than the 30-year rotation. Diameter limit cutting (20 cm lower limit for all species) every 9 years, on the other hand, results in yields nearly as high as clearcutting and higher than any 30- or 45-year intensive harvest rotation tested. A 40 cm lower limit reduced yields somewhat. An important factor in these results is the absence of a shrub layer in the model. Tolerant shrubs and beech sprouts have been shown to severely limit tree reproduction under partial cutting in this forest type (Barrett and other 1962, Curtis and Rushmore 1958). Only slight modifications in the model would be required to include this shrub layer.

Selective removal of species can also be simulated. For example, not all clearcuts in this region come back mainly to pin cherry. We simulated succession after whole tree harvesting without pin cherry to test its effect on total yield. Table 2 contains results for 9-, 30-, and 90-year rotations without pin cherry. Its removal increased yield in the two longer rotations but not in the 9-year regime. The increases are due to having less of the earliest production go into pin cherry stems which will die before harvest. When the rotation length is shorter than pin cherry's life span, its presence increases yields, although harvesting on this short a rotation causes severe reductions in the forest floor. It is interesting that this life-history factor was more important than the cherry's role in increasing total production and litter fall and thereby speeding recovery of the forest floor (Marks and Bormann 1972). Forest floor biomass was always greater with pin cherry present.

Creation of single species stands can be simulated by altering the diameter limit for cutting parameter for different species. For example, a 9-year rotation with a 20 cm lower limit for yellow birch and 0 cm for all other species creates a solid yellow birch stand after about 40 years. Continuing this harvesting regime every 9 years produces quite low yields without fertilization due to low forest floor biomass and nitrogen availability resulting from low total leaf biomass and increased decomposition rates. The same procedure with selection for sugar maple instead of yellow birch produces higher yields.

Could fertilization ameliorate some of the negative impacts of short rotations? FORTNITE can make predictions on effects of increased nitrogen availability but a strict relationship to fertilizer applications is tenuous. For example, it is unclear what the efficiency of fertilizer retention is within a forest ecosystem. Thus, an application of 100 kg/ha of nitrogen may not be equivalent to a similar increase in mineralization from soil organic matter. In addition, there is generally a carry over in growth response lasting 5 years or longer to a single fertilizer application. This may be due to secondary increases in mineralization in the presence of nitrogen enriched litter or to storage and reuse by trees through retranslocation before litter fall. Neither of these factors are currently modeled in FORTNITE.

We have made the most generous assumptions and treated the potential effects of fertilization on yield. We assumed 100 percent efficiency in fertilizer use and an exponentially declining effect lasting 5 years. So, if a stand receives 100 kg/ha in year 15, then a residual effective increase in available nitrogen of 50 kg/ha is assumed in year 16, 25 kg/ha in year 17, 12.5 kg/ha in year 18, and 6.25 kg/ha in year 19. Table 2 shows results for fertilization on previously tested regimes. The "one N addition/30 yrs" treatment means fertilizations in years 25, 55, and 85. The "two N additions/30 yrs" treatment receives an additional 100 kg/ha in years 15, 45, and 75.

Increases in yields with fertilization are quite large under certain conditions. For example, whole tree harvesting on a 30-year rotation with two fertilization treatments per 30 years approaches a single 90-year whole tree rotation but is still far short of a 90-year rotation with two fertilizations per 30 years. The increases in yield for the yellow birch selection regime are the most dramatic. The highest yield of any treatment is achieved under selection for yellow birch with two fertilizations each 30-year period. This is clearly one of the most intensive treatments as well, requiring fertilization plus weeding along with each harvest, and may not be practical. Accurate economic projections of the future costs associated with each of these treatments is required to assess their cost effectiveness. The quantitative yield predictions possible with FORTNITE could be linked with an economic analysis routine to provide a powerful management tool for this or other forest types.

CONCLUSIONS

We have described the outline, structure, and predictions of a detailed, process-oriented model of organic matter and nitrogen dynamics in forested ecosystem as applied to the northern hardwood forest type of northern New England. Such a model is never really completed. New data on parts of the system currently poorly understood will cause continuous changes in the data base and probably the structure of FORTNITE. This could result in some major changes in the predictions given here. Still, FORTNITE represents a quantitative synthesis of the processes affecting production, decomposition, and nitrogen cycling in this forest type as represented by the current state of our knowledge. Dismissal of its conclusions must be based on disagreement with either the structure or the data base employed. There is room for dispute with both, from which should emerge new ideas, new research, and eventually an improved quantitative understanding of forest ecosystems.

LITERATURE CITED

ABER, J. D. 1976. A computer model of canopy dynamics and competition for light and nutrients in northern hardwoods. PhD thesis, Yale Univ. 182 p. (Diss Abstr 77-10857.)

ABER, J. D., and J. M. MELILLO. 1980. Litter decomposition: measuring relative contributions of organic matter and nitrogen to forest soils. Can J Bot 58:416–421.

ABER, J. D., and J. M. MELILLO. 1982a. Nitrogen immobilization in decaying hardwood leaf litter as a function of initial nitrogen and lignin content. Can J Bot: In press.

ABER, J. D., and J. M. MELILLO. 1982b. FORTNITE: An integrated computer model of organic matter and nitrogen dynamics in forest ecosystems. Univ Wis Res Bull: In press.

ABER, J. D., D. B. BOTKIN, and J. M. MELILLO. 1978. Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. Can J Forest Res 8:306–315.

ABER, J. D., D. B. BOTKIN, and J. M. MELILLO. 1979. Predicting the effects of different harvesting regimes on productivity and yield in northern hardwoods. Can J Forest Res 9:10–14.

BARRETT, J. W., C. E. FARNSWORTH, and W. RUTHERFORD. 1962. Logging effects on regeneration and certain aspects of microclimate in northern hardwoods. J For 60:630–639.

BORMANN, F. H., and G. E. LIKENS. 1979. Pattern and process in a forested ecosystem. Springer-Verlag, New York. 253 p.

BORMANN, F. H., G. E. LIKENS, T. G. SECCAMA, R. S. PIERCE, and J. S. EATON. 1974. The export of nutrients and recovery of stable conditions following deforestation of Hubbard Brook. Ecol Monogr 44:255–277.

BOTKIN, D. B., J. F. JANAK, and J. R. WALLIS. 1972. Some ecological consequences of a computer model of forest growth. J Ecol 60:849–872.

CHRISTENSEN, O. 1977. Estimation of standing crop and turnover of dead wood in a Danish oak forest. Oikos 28:177–186.

COVINGTON, W. W. 1981. Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwoods. Ecology 62:41–48.

COVINGTON, W. W., and J. D. ABER. 1980. Leaf production during secondary succession in northern hardwoods. Ecology 61:200–204.

CURTIS, R. O., and BOYD W. POST. 1964. Basal area, volume and diameter related to site index and age in unmanaged even-aged northern hardwoods in the Green Mountains. J For 62:864–870.

CURTIS, R. O., and F. M. RUSHMORE. 1958. Some effects of stand density and deer browsing on reproduction in an Adirondack hardwood stand. J For 56:116–121.

DALE, M. E. 1974. Individual tree growth and simulation of stand development of an 80 year old white oak stand. *In* Forest modeling and inventory (A. R. Ek, J. W. Balsiger, and L. C. Promnitz, eds), p 49–63. Univ Wis, Dep For, Madison. 122 p.

ESHLEMAN, K. N., J. D. ABER, and J. M. MELILLO. 1979. The role of wood decomposition in nitrogen cycling of forest ecosystems. Bull Ecol Soc Am 60(2):97.

ESHLEMAN, K. N., J. M. MELILLO, and J. D. ABER. 1980. Nitrogen immobilization potential of decomposing wood fragments in a forest soil. Bull Ecol Soc Am 61(2):114.

EYRE, F. H., and W. M. ZILLGITT. 1953. Partial cuttings in northern hardwoods of the Lake States. US Dep Agric Tech Bull 1076, 124 p.

LEAK, W. B. 1979. Effects of habitat on stand productivity in the White Mountains of New Hampshire, USDA Forest Serv Res Pap NE-452, 8 p.

LEAK, W. B., and R. W. WILSON. 1958. Regeneration after cutting of old growth northern hardwoods in New Hampshire. USDA Forest Serv, Northeast Forest Exp Stn, Stn Pap 103, 8 p.

LEAK, W. B., D. S. SOLOMON, and S. M. FILIP. 1969. A silvicultural guide for northern hardwoods in the northeast. USDA Forest Serv Res Pap NE-143, 34 p.

LIKENS, G. E., F. H. BORMANN, R. S. PIERCE, J. S. EATON, and N. M. JOHNSON. 1977. Biogeochemistry of a forested ecosystem. Springer-Verlag, New York. 146 p.

MARKS, P. L. 1974. The role of pin cherry (*Prunus pennsylvanica* L.) in the maintenance of stability in northern hardwood ecosystems. Ecol Mono 44:73–88.

Marks, P. L., and F. H. Bormann. 1972. Revegetation following forest cutting: mechanisms for return to steady-state nutrient cycling. Science 176:914–915.

Marquis, D. A. 1965. Regeneration of birch and associated hardwoods after patch cutting. USDA Forest Serv Pap NE-32, 13 p.

Marquis, D. A. 1967. Clearcutting in northern hardwoods: results after 30 years. USDA Forest Serv Res Pap NE-85, 13 p.

McClaugherty, C. A., J. D. Aber, and J. M. Melillo. 1980. Analysis of fine root dynamics in forest ecosystems. Bull Ecol Soc 61(2):113.

Melillo, J. M., J. D. Aber, and J. M. Muratore. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology: In press.

Mitchell, H. L., and R. F. Chandler. 1939. The nitrogen nutrition and growth of certain deciduous trees of northeastern United States. Black Rock Forest Bull 11, 94 p.

Monserud, R. A. 1976. Simulation of forest tree mortality. Forest Sci 22:438–444.

Monsi, M., Z. Uchijima, and T. Olkawa. 1973. Structure of foliage canopies and photosynthesis. Annu Rev Ecol Syst 4:301–327.

Roskoski, J. P. 1980. Nitrogen fixation in hardwood forests of the northeastern United States. Plant and Soil 54:33–44.

Shugart, H. H., Jr., and D. C. West. 1980. Forest succession models. Bioscience 30:308–313.

USDA Forest Service. 1965. Silvics of forest trees of the United States. US Dep Agric, Agric Handb 271, 762 p.

Waide, J. B., and W. T. Swank. 1977. Simulation of potential effects of forest utilization on the nitrogen cycle in different southeastern ecosystems. *In* Watershed research in North America (Correll, ed), p 767–789. Smithson Inst, Edgewater, Md.

Whittaker, R. H., F. H. Bormann, G. E. Likens, and T. G. Siccama. 1974. The Hubbard Brook ecosystem study: forest biomass and production. Ecol Monogr 44:233–254.